Small-x collective effects in eA scattering

Vadim Guzey

Petersburg Nuclear Physics Institute (PNPI),
National Research Center "Kurchatov Institute",
Gatchina, Russia

Outline:

- Basics of nuclear shadowing
- Leading twist nuclear shadowing
- Gluon shadowing from charmonium photoproduction at the LHC
- Conclusions

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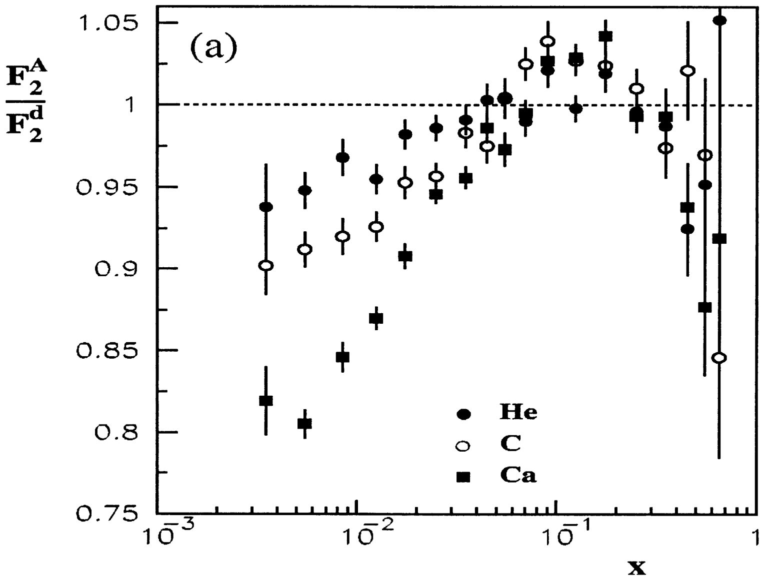
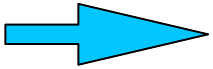
Nuclear shadowing: data and global fits

- Nuclear shadowing = high-energy (small x) collective/coherent nuclear effect: $F_{2A}(x,Q^2) < A\, F_{2N}(x,Q^2) \rightarrow g_A(x,Q^2) < A\, g_N(x,Q^2)$

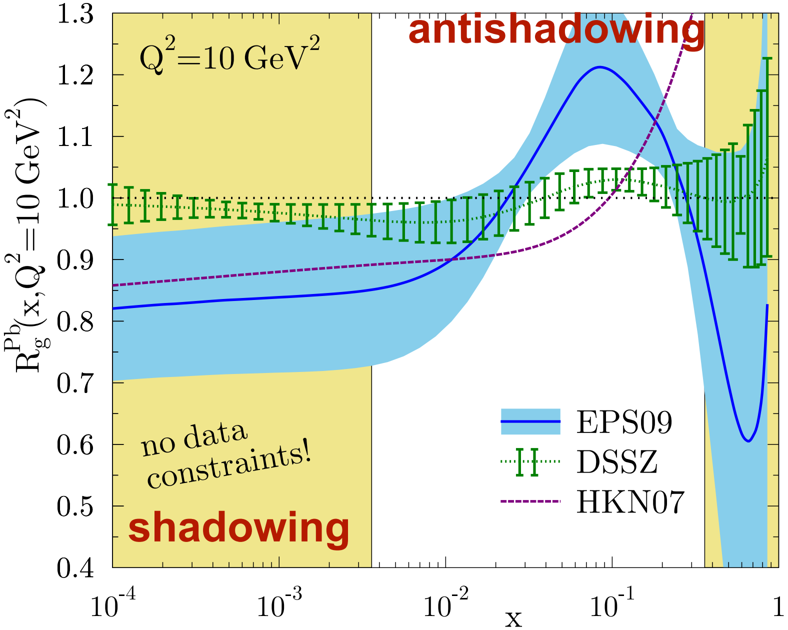
Piller, Weise (2000)



Global QCD fits



H. Pauukunen, NPA 926 (2014) 24



- Nuclear PDFs, especially $g_A(x,\mu^2)$, are known with large uncertainties.
- Small-x, small-Q^2 fixed-target data may contain large HT effects, Qiu, Vitev, 2004
- pA@LHC data help mostly in antishadowing region, Armesto et al, arXiv:1512.01528; Eskola et al, JHEP 1310 (2013) 213
- Future options: Electron-Ion Collider in the US, Accardi et al, ArXiv:1212.1701; LHeC@CERN, LHEC Study Group, J. Phys. G39 (2012) 075001
- Option right now: Charmonium photoproduction in Pb-Pb UPCs@LHC

Nuclear shadowing: Gribov-Glauber model

- At high-energies, probe interacts *coherently (collectively)* with all nucleons of the nucleus target.

- Shadowing is a result of destructive interference of amplitudes for the interaction with 1, 2, 3, etc. nucleons of the target.

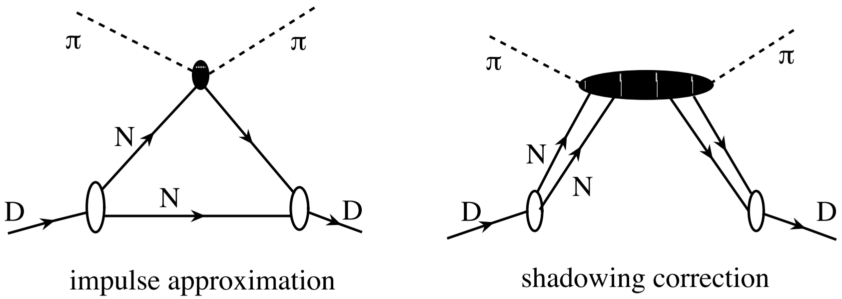


Figure 2: Graphs for pion-deuteron scattering.

- Intermediate states are elastic (Glauber) and elastic+inelastic (Gribov), Glauber 1955, Gribov, 1969 ⟶ nuclear shadowing is driven by elementary diffraction

- For nucleon beams, elastic dominates → Glauber model for total, elastic, inelastic pA and nA cross sections with % accuracy.

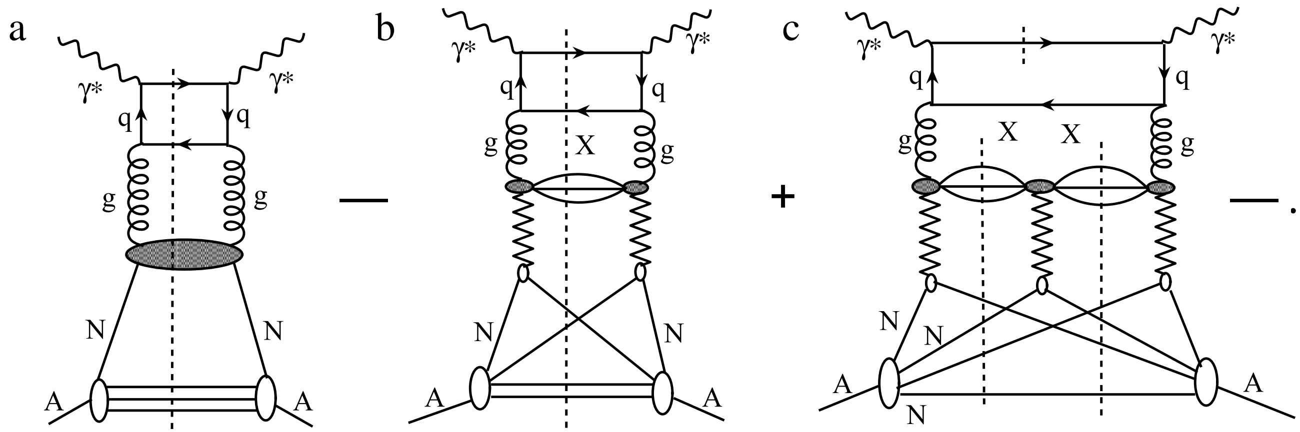
- For γ (γ*), diffraction into large masses is 40% (~100%) of diffr. dissociation cross section → shadowing driven by multiple rescatterings of effective cross section:

$$\sigma_{\rm eff} = \frac{16\pi}{\sigma_{\gamma^* N}} \int dM_X^2 \frac{d\sigma^{\rm diff}_{\gamma^* N}(t=0)}{dM_X^2 dt}$$

- Good description of total γA and γ*A cross sections, Frankfurt, Strikman 1999; Adeluyi, Fai 2006; Capella et al (1997); Armesto et al (2003); Tywoniuk et al (2006)

Leading twist nuclear shadowing model

- For γ^*, one can combine Gribov-Glauber model with QCD factorization theorems for inclusive and diffractive DIS → shadowing for individual partons j, Frankfurt, Strikman (1999)



- Interaction with 2 nucleons: model-indep via diffractive PDFs: $$\sigma_2^j(x) = \frac{16\pi}{x f_{j/N}(x,\mu^2)} \int_x^{0.1} dx_P \beta f_{j/N}^{D(4)}(x,\mu^2,x_P,t=0)$$

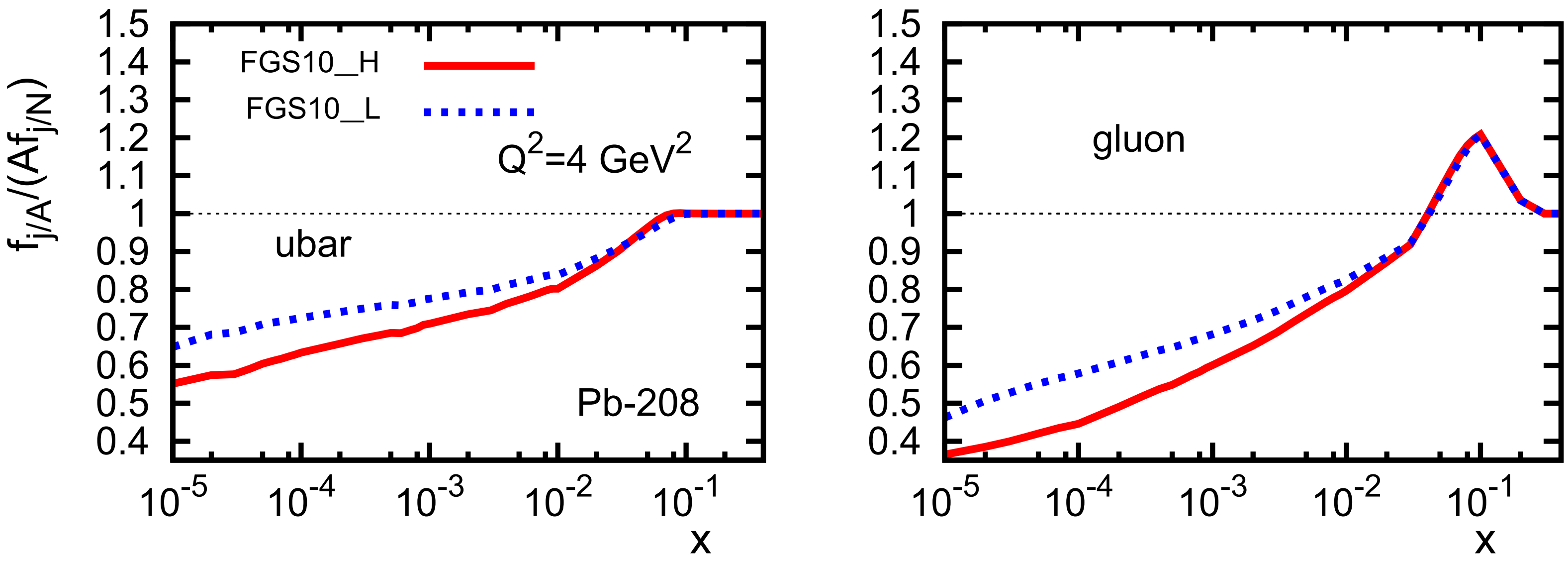
- Interaction with ≥ 3 nucleons: via soft hadronic fluctuations of γ^* $$\sigma_{\rm soft}(x) = \frac{\int d\sigma P_\gamma(\sigma)\sigma^3}{\int d\sigma P_\gamma(\sigma)\sigma^2}$$ P(σ) probability to interact with cs σ

- In quasi-eikonal approximation in low-x limit, Frankfurt, Guzey, Strikman 2012:

$$x f_{j/A}(x,\mu^2) = A f_{j/N}(x,\mu^2) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\rm soft}^j(x)]^2} \int d^2b \left(e^{-\frac{1}{2}\sigma_{\rm soft}^j(x) T_A(b)} - 1 + \frac{\sigma_{\rm soft}^j(x)}{2} T_A(b) \right)$$

Leading twist nuclear shadowing model (2)

- Model gives input NLO nuclear PDFs at μ^2=4 GeV^2 for subsequent DGLAP evolution.



- Antishadowing for gluons only, “by hand” requiring momentum sum rule conservation.

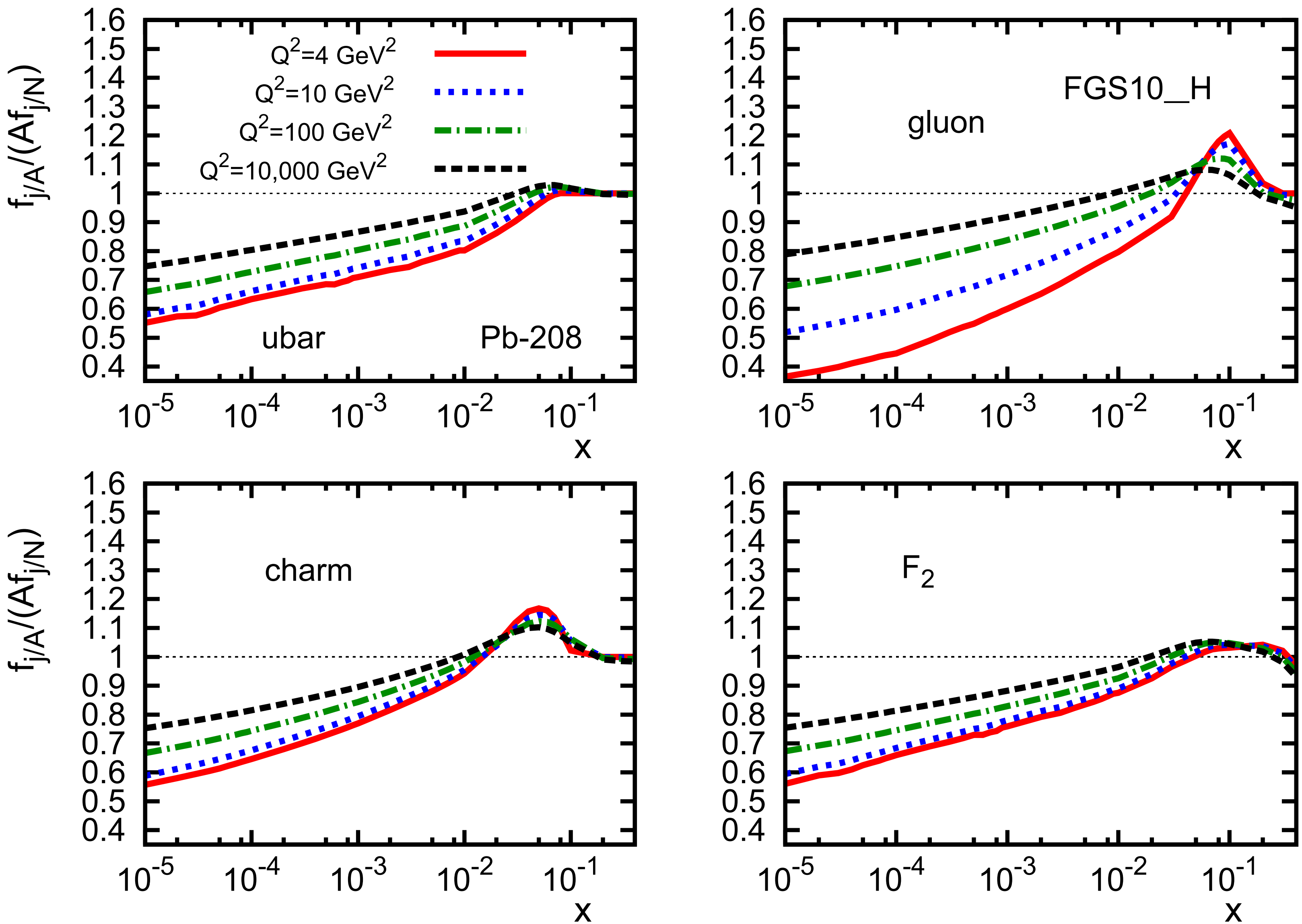
- Name “*leading twist”* because diffractive structure functions/PDFs measured at HERA scale with Q^2, i.e., LT quantity.

- Main theoretical uncertainty from σ_{soft}

- Absent in case of deuteron → can be used to test the LT shadowing approach.

Leading twist nuclear shadowing model (3)

- Results of NLO DGLAP evolution using LT nuclear shadowing input:

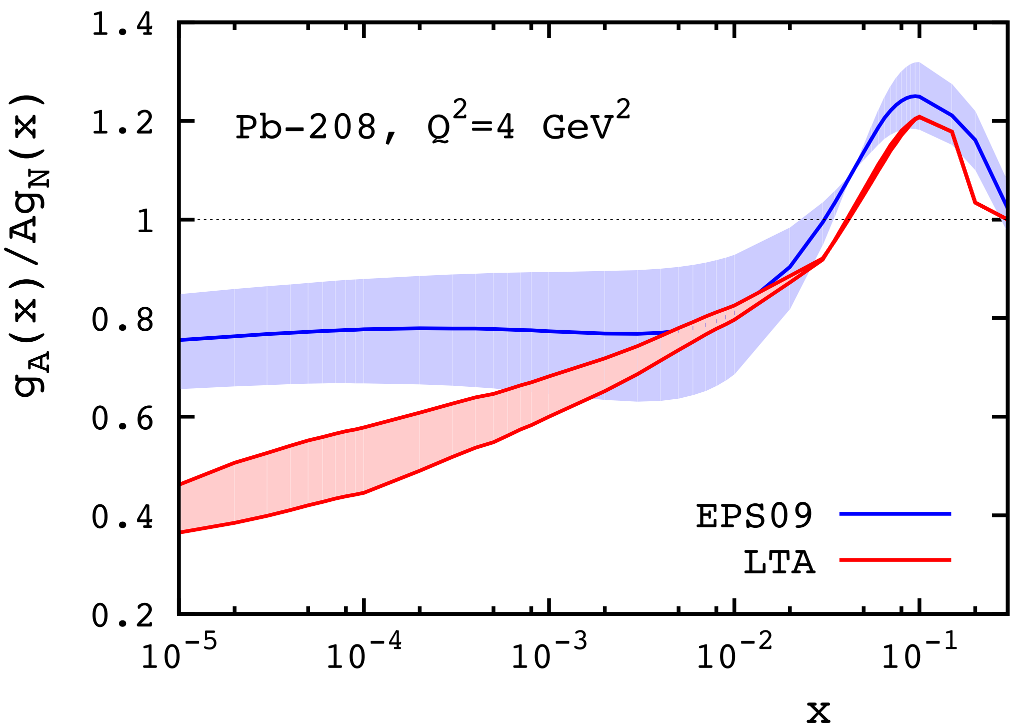


Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

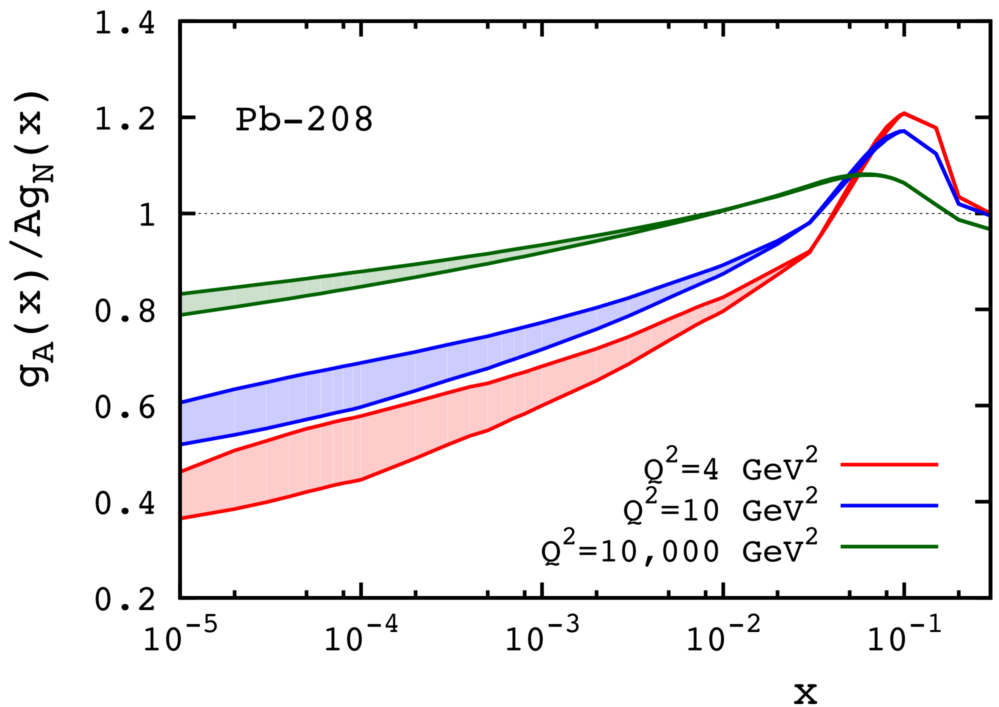
Leading twist nuclear shadowing model (4)

- Gluon diffractive PDFs are large, ZEUS, H1 2006 → large shadowing for $g_A(x,\mu^2)$, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Input: Leading twist (LTA) vs. EPS09



Results of DGLAP evolution: from Q^2=4 GeV^2 to Q^2=10 and 10,000 GeV^2

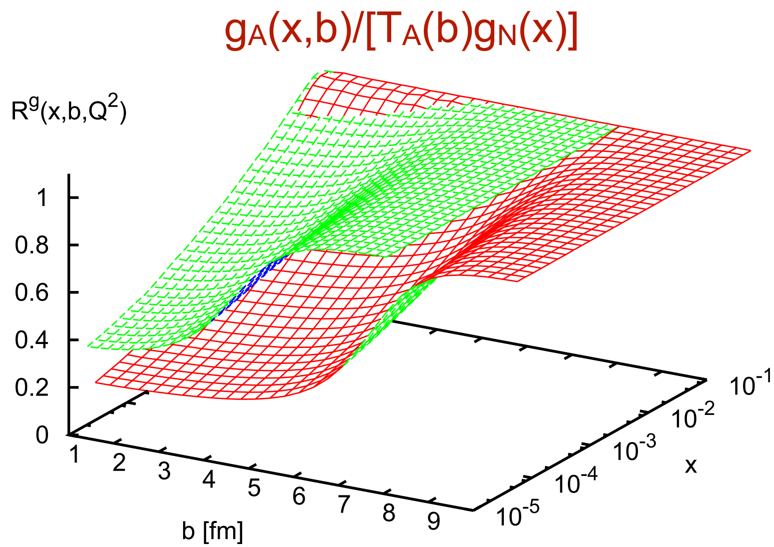


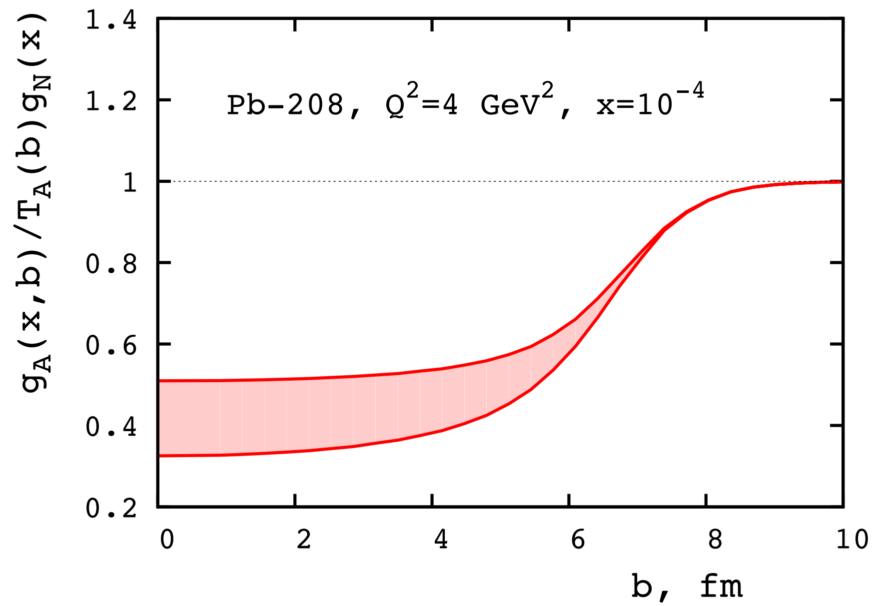
For quarks, the agreement between LTA and EPS09 is much better.

LT shadowing: Impact parameter dependence

- Shadowing arises from rescattering on target nucleons at given impact parameter b.
- Removing integral over b → impact parameter dependent nuclear PDFs:

$$x f_{j/A}(x,b,\mu^2) = T_A(b) x f_{j/N}(x) - \frac{2\sigma_2^j f_{j/N}(x,\mu^2)}{[\sigma_{\rm soft}^j(x)]^2}\left(e^{-\frac{1}{2}\sigma_{\rm soft}^j(x)T_A(b)} - 1 + \frac{\sigma_{\rm soft}^j(x)}{2}T_A(b)\right)$$

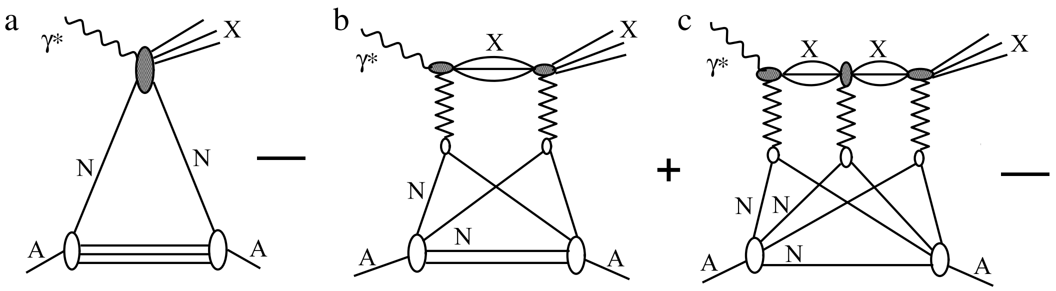




- Can be only indirectly determined using global QCD fits, EPS09s nPDFs, Helenius et al (2012)
- Can be probed and tested in:
  - centrality dependence of hard pA/AA processes, Helenius et al (2012)
  - *t* dependence of exclusive γ^*A and γA processes, e.g., $\gamma^*A \to \gamma A$, Frankfurt, VG, Strikman 2012, $\gamma A \to J/\psi A$, VG, Strikman, Zhalov, work in progress

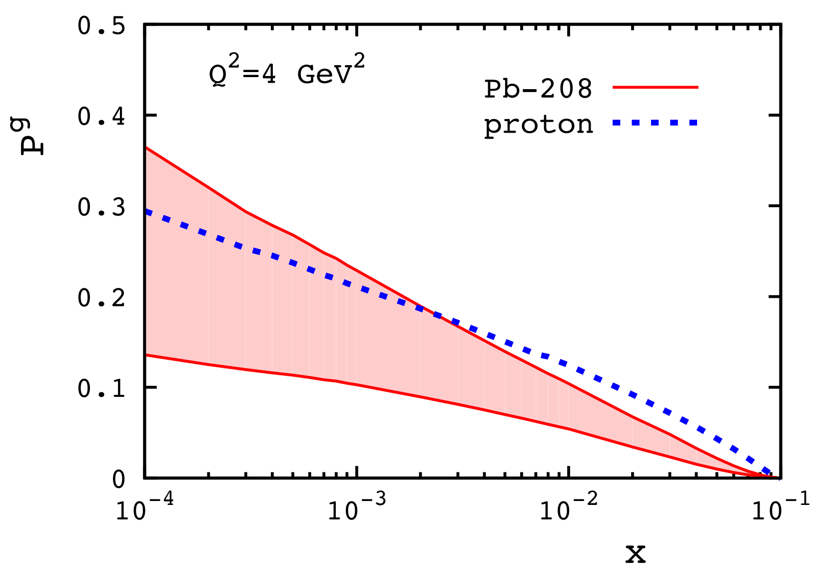
Nuclear diffractive parton distributions

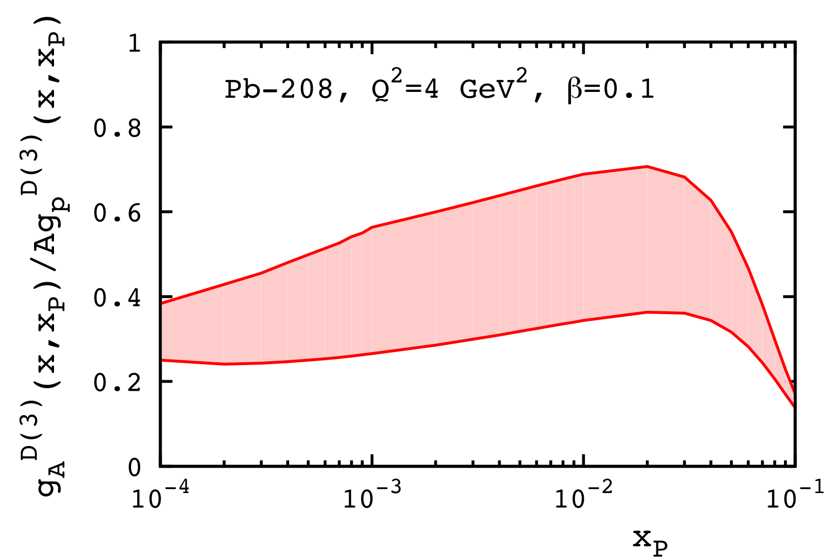
- Leading twist nuclear shadowing model can be applied to inclusive diffraction in γ^*A:



$$\beta f_{j/A}^{D(3)}(x,\mu^2,x_P) = 16\pi f_{j/N}^{D(4)}(x,\mu^2,x_P,t=0)\int d^2b\left(\frac{1-e^{-\frac{1}{2}\sigma_{\text{soft}}^j(x)T_A(b)}}{\sigma_{\text{soft}}^j(x)}\right)^2$$

- Predicted large probability of hard diffraction on nuclei and nuclear diffractive PDFs:





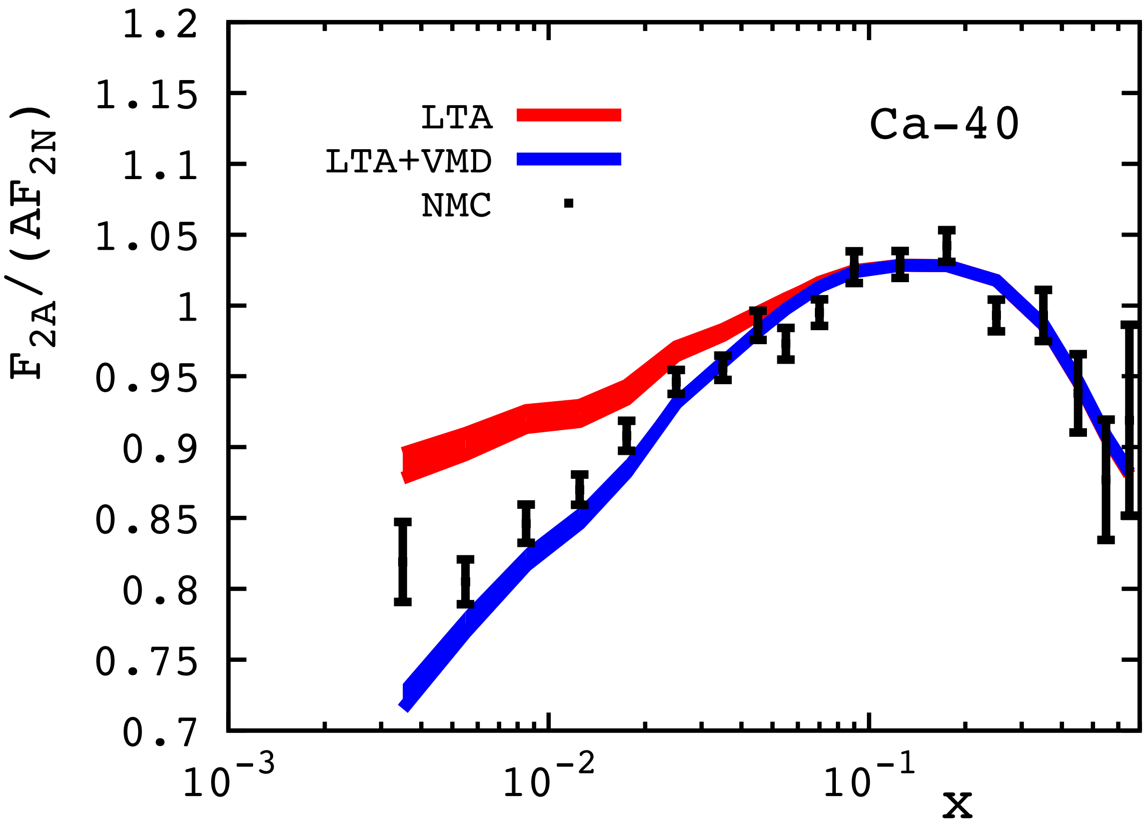
- Can be measured in inclusive γ^*A diffraction at LHeC/EIC and hard diffraction in γA, e.g., diffractive photoproduction of dijets in UPCs@LHC, Guzey, Klasen 2016

Leading twist vs. all-twist shadowing

- In our leading twist shadowing model, we take $\mu^2=4\ \mathrm{GeV}^2$ to minimize (i) HT effects in diffractive PDFs, H1, ZEUS, 2006, (ii) cross section fluctuation in γ^*

- We underestimate shadowing at fixed-target energies

Comparison of theoretical predictions: Leading twist model (LTA) and LT+HT (ρ, ω, and ϕ vector mesons) to NMC 1995 fixed-target data.



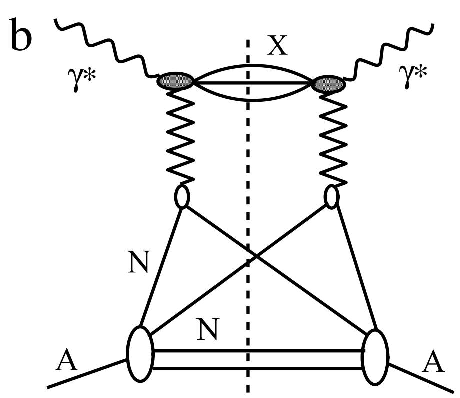
→ HT effects may contaminate global QCD fits of nuclear PDFs.

Leading twist vs. higher-twist shadowing

- Principal difference between our LTA and all-twist approaches, e.g. dipole model:

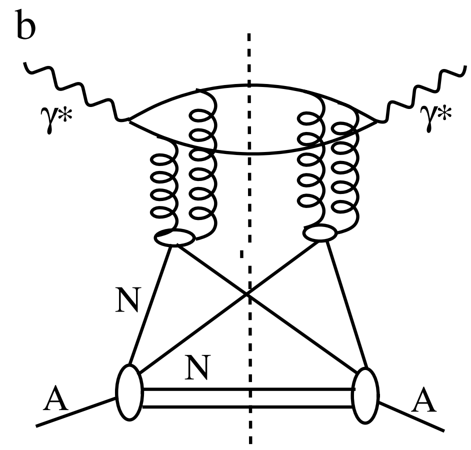
Frankfurt, Guzey, McDermott, Strikman 2002

Triple-Pomeron coupling to 2 nucleons



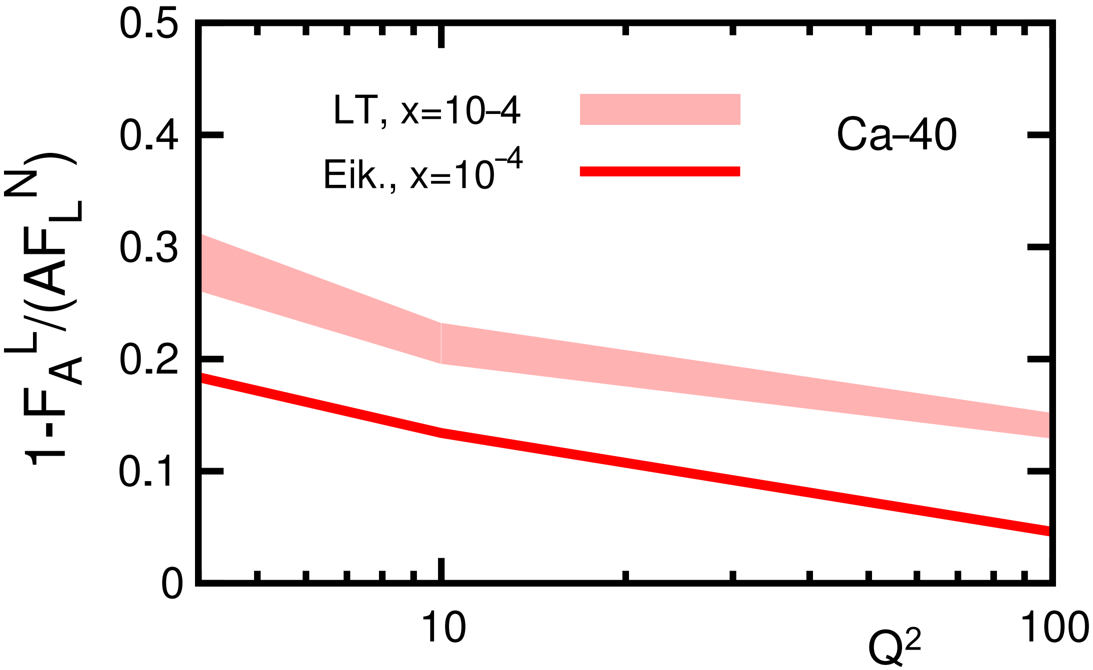
vs.

Separate Pomeron couplings to 2 nucleons → higher twist (HT) for small dipoles



- The difference should manifest itself in observables dominated by small-size dipoles:

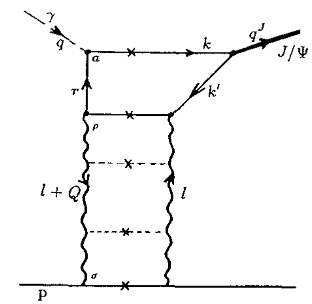
- nuclear longitudinal structure function $F_L^A(x,Q^2)$ at LHeC/EIC
- nuclear suppression of J/ψ photoproduction on nuclei in UPCs@LHC



Exclusive charmonium photoproduction

• To leading order in α_S and in non-relativistic approximation for charmonium (J/ψ, $\psi(2S)$) distribution amplitude:

$$\frac{d\sigma_{\gamma T\to J/\psi T}(W,t=0)}{dt}=\frac{16\pi^3\Gamma_{ee}}{3\alpha_{\rm e.m.}M_V^5}\boxed{\left[\alpha_S(\mu^2)H^g(\xi,\xi,t=0,\mu^2)\right]^2}$$



M. Ryskin (1993)

• At LO and small ξ, GPDs are expressed in terms of PDFs:

$$\boxed{H^g(\xi,\xi,t=0,\mu^2)=R_g xg(x_B,\mu^2)}$$

$$R_g=\frac{2^{2\lambda+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda+5/2)}{\Gamma(4+\lambda)}\approx 1.2,\ \text{for } xg\sim 1/x^{\lambda} \text{ with } \lambda\approx 0.2$$

• Application to nuclear targets:

$$\sigma_{\gamma A\to J/\psi A}(W_{\gamma p})=\frac{(1+\eta_A^2)R_{g,A}^2}{(1+\eta^2)R_g^2}\frac{d\sigma_{\gamma p\to J/\psi p}(W_{\gamma p},t=0)}{dt}\left[\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)}\right]^2\Phi_A(t_{\rm min})$$

Small correction $k_{A/N}\approx 0.95$

From HERA and LHCb

Gluon shadow. Rg

From nuclear form factor

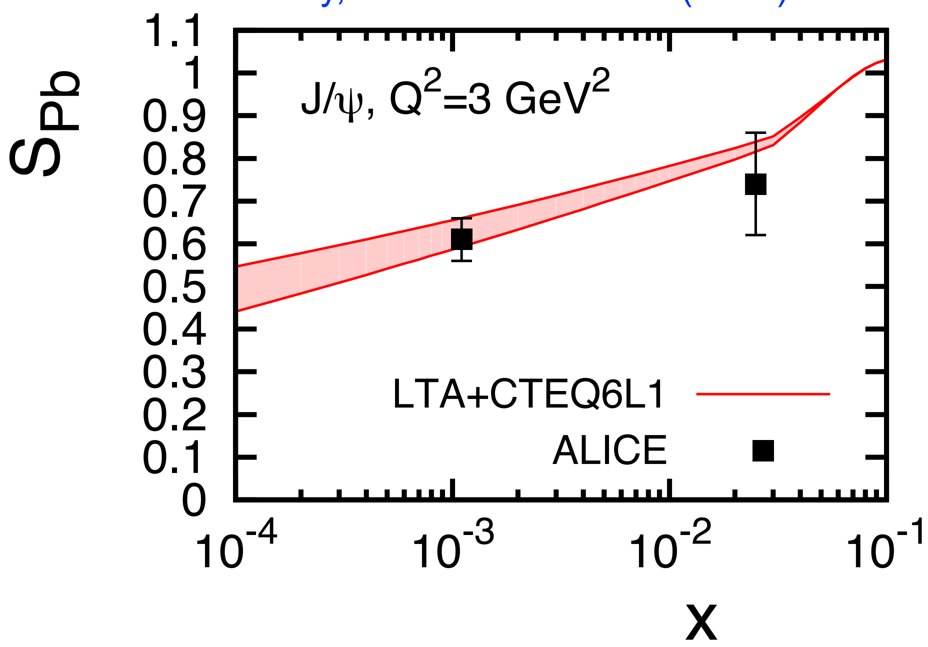
$$\Phi_A(t_{\rm min})=\int_{-\infty}^{t_{\rm min}}dt|F_A(t)|^2$$

Comparison to ALICE and CMS UPC data

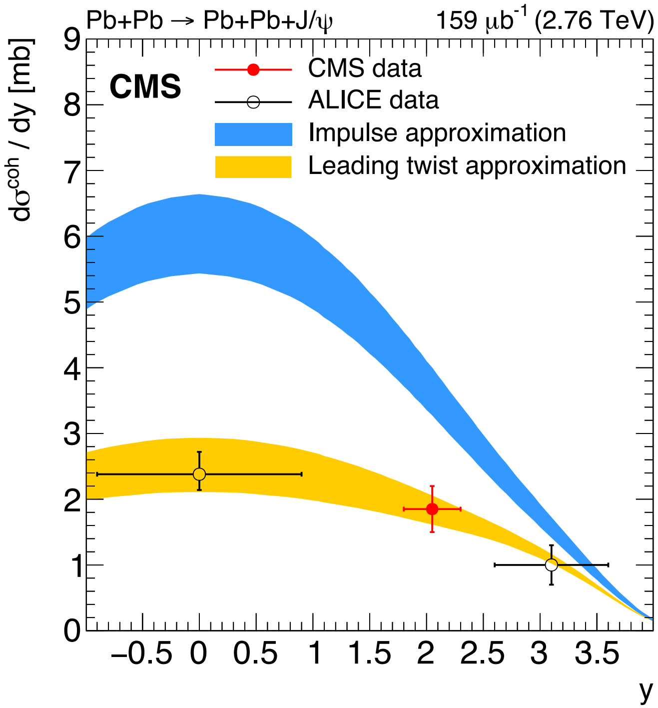
• Nuclear suppression factor S:

$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb\to J/\psi Pb}}{\sigma^{\rm IA}_{\gamma Pb\to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)} = \kappa_{A/N}R_g$$

Guzey, Zhalov JHEP 1310 (2013) 207



Abelev *et al*. [ALICE], PLB718 (2013) 1273;
Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617



[CMS], arXiv:1605.06966 [nucl-ex]

• Good agreement with ALICE data on coherent J/ψ photoproduction in Pb-Pb UPCs@2.76 TeV → first direct evidence of large gluon nuclear shadowing at x=0.001.

• Similarly good description using EPS09+CTEQ6L.

• Cannot be described by simple versions of the dipole model, Lappi, Mantysaari 2013

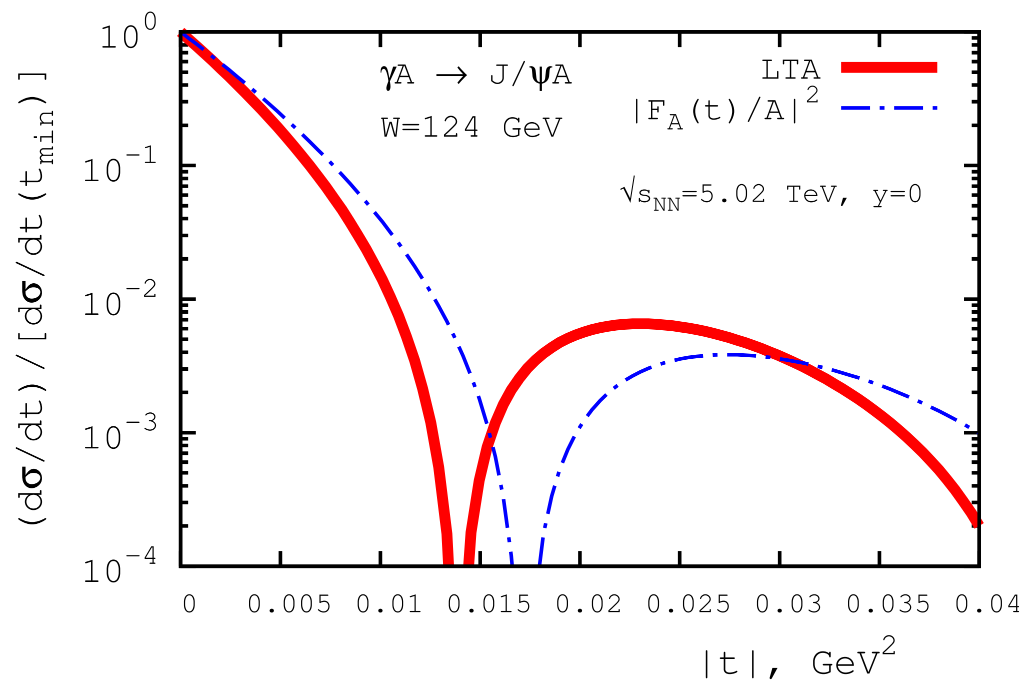
Transverse imaging of nuclear gluon distributions

• Nuclear shadowing does not only suppress the $\gamma A \rightarrow J/\psi A$ cross section, but also modifies its t dependence.

$$\frac{d\sigma_{\gamma A\rightarrow J/\psi A}}{dt} = \frac{d\sigma_{\gamma p\rightarrow J/\psi p}(t=0)}{dt}\left(\frac{R_{g,A}}{R_{g,p}}\right)^2 \left(\frac{g_A(x,t,\mu^2)}{Ag_p(x,\mu^2)}\right)^2$$

• Nuclear GPD in ξ=0 limit ↔ impact parameter dependent nuclear PDF

$$g_A(x,t,\mu^2) = \int d^2\vec{b}\, e^{i\vec{q}_\perp \vec{b}} g_A(x,b,\mu^2)$$



Guzey, Strikman, Zhalov, work in progress

• Shift of t-dependence is caused by broadening in transverse plane of nuclear gluon distribution due to nuclear shadowing → $\Delta R_A/R_A \approx 1.05\text{-}1.11$.

Conclusions

• Nuclear PDFs at small x are poorly constrained, especially in gluon channel.

• Leading twist nuclear shadowing model is a dynamical approach to nuclear PDFs and nuclear diffractive PDFs at small x, whose phenomenology requires only a few weakly-constrained parameters.

• The approach makes definite predictions for x, Q2 and b dependence of nPDFs in the collider kinematics of LHC, LHeC and EIC, where results of global QCD fits are an extrapolation.

• Predicted large nuclear gluon shadowing is confirmed by ALICE and CMS measurements of coherent J/ψ photoproduction on Pb in UPCs@LHC.